Fast Simulations of 3D Axial Switched Reluctance Motor Drives

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Abstract — **Estimation of functional parameters such as absolute torque, torque ripple or axial forces, are of great interest whilst the design process of a switched reluctance motor drive (SRM). Especially the axial construction form was not studied in detail in the past. This paper describes the results and procedure of the so called quasi transient simulation of an SRM, which is based on a nonlinear-magnetic, full field, time efficient and accurate finite element simulation (FEM).**

Index Terms—**Finite element methods, reluctance motor drives, switched circuits**

I. INTRODUCTION

A switched reluctance motor (SRM) is an electric motor in which torque is produced by the tendency of its moveable part (rotor) to move to a position where the reluctance of the whole system is minimized (Fig. 1). The example geometry shows the position of minimum reluctance i.e. the blue windings are supplied by a current I_0. The SRM is a type of synchronous machine without any coils or magnets on its rotor. The origin of this motor can be traced back to 1842, but it was reinvented due to the advantages, i.e. its high power density at low cost, the big range of rotational speed and its high efficiency [1-2]. The results presented in the paper are all from an actual drive which was built at the Ilmenau University of Technology (Ilmenau, Germany) in cooperation with Mahle (Crock, Germany), driveXpert (Ilmenau, Germany), Melexis GmbH (Erfurt, Germany) and Magnet World (Jena, Germany).
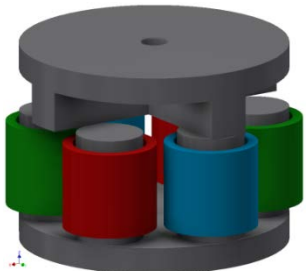

Fig. 1. Sample-model of 6/4 pole axial switched reluctance motor (A-SRM, 6 stator and 4 rotor poles)

II. DESCRIPTION OF METHODS

A. Theory

An electric current I_0 flowing through stator windings as illustrated in the form of pairwise colored cylinder rings (Fig. 1) generates a magnetic flux density **B**, which can be modeled by means of a magnetic vector potential **A**. This flux is highly concentrated inside the motor material due to its ferromagnetic characteristics. A full transient solution of the given field problem has to take the generation of eddy currents by induction inside the conducting material into account. Eddy currents are generated by (i) a time changing magnetic field $-\partial \mathbf{B}/\partial t$ and (ii) relative motion between conducting objects i.e. rotor and stator $\mathbf{v} \times \mathbf{B}$. In the general case, magnetic field can be described by means of potentials as:

$$\nabla \times \left(\frac{1}{\mu_0} \nabla \times \mathbf{A} \right) = \underbrace{-\sigma \left(\frac{\partial \mathbf{A}}{\partial t} + \nabla V - \mathbf{v} \times \nabla \times \mathbf{A} \right)}_{\mathbf{j}} + \mathbf{j}_e \quad (1)$$

where V denotes the scalar electric potential, $\mathbf{j_e}$ and $\mathbf{j}$ are the external and induced current density respectively, and **v** is the velocity of the rotor.

B. Motor material

In the case of axial SRMs as presented in [3] and [4] it is not possible to use a sheeted structure in order to reduce eddy current effects. Therefore the conductivity of the material has to be as low as possible. Therefore, a soft magnetic composite material (SMC) was used for rotor and stator. This material shows a nonlinear and hysteretic behavior. In our simulations, any hysteresis effects were neglected and the initial magnetization curve of the material was used instead.

C. Quasi-transient and superposition approach

In the quasi-transient approach (QT), we simplified the problem by the following assumptions: (i) eddy current effects due to time changing magnetic fields can be neglected because of a low conductivity of the SMC, which is in a range between 10^3-10^4 S/m; (ii) eddy current effects due to relative motion between rotor and stator are neglected as well; and (iii) hysteresis of the nonlinear magnetic material is not taken into account. This enables to simplify the simulations to a stationary field problem which leads to a remarkable reduction of degrees of freedom (DOF) and time to solve.

The other approach which can be applied in simulations of the SRM is the principle of superposition (SUP). In this case, only one pass from the unaligned to the aligned rotor position is needed to estimate the full transient waveform of a functional parameter, like absolute torque or axial force. However, this approach leads to inaccuracies when applied to non-linear magnetic materials since it is only valid for linear problems.

D. Current switching strategies

Several switching strategies exist to control SRMs which significantly influence the qualities of the motor. In this paper we propose two different approaches, the so called PPP and NPN supply scheme (Fig. 2), where "P" and "N" denote positive and negative current directions inside the coil windings respectively. The amplitude of the current was I_{max} for a period of $\beta_{on} = 45°$ which results in the case of a 6/4 SRM in an overlap of $\chi = 15°$ between two adjacent switching cycles.
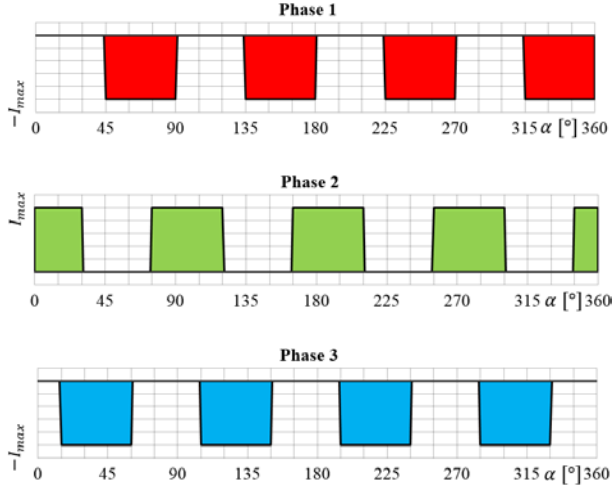

Fig. 2. NPN supply scheme for quasi-transient analysis.

III. RESULTS AND DISCUSSION

One complete and symmetric torque cycle, beginning from the unaligned position at -45° over the aligned position at 0° back to the unaligned position at +45° is illustrated in Fig. 3.
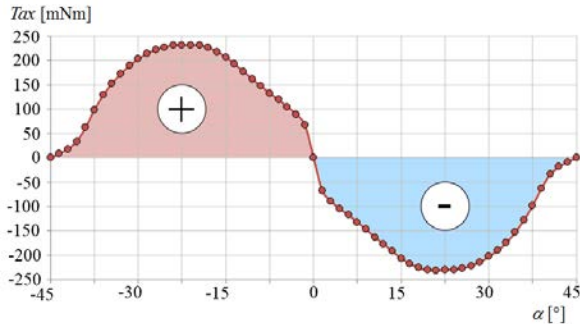

Fig. 3. Single phase torque profile used in SUP analysis - only one phase of stator is supplied.

We used these torque values for the construction of the transient torque in the SUP approach. The transient torque is a sum of signals shifted according the PPP scheme (Fig. 4). In contrast, the QT analysis was performed under the assumption that all phases are supplied using PPP/NPN scheme. The results are shown in Fig. 5. We can observe that SUP torque profile is closer to the torque profile received by QT analysis for the NPN supply scheme than for the PPP scheme. The corresponding normalized root mean squared deviations (NRMSD) equal 2.6% and 4.75% respectively. The overestimated torque from SUP can be explained by saturation effects and the associated superposition inaccuracy.

IV. CONCLUSIONS

Two methods are proposed which enable simplified and fast transient simulations of SRM. Especially in case of axial motor designs, it is necessary to reduce computational cost in order to perform parameter studies to improve the given design. The full paper will compare QT analysis and SUP with measurements and time consuming transient simulations (1)-(2) without the given simplifications. It is expected, that the presence of eddy currents will affect the functional parameters of SRM. The real transient simulation in the time domain requires a correct definition of phase currents, i.e. the implementation of external controlling electric circuits. In consequence, all these modifications increase the DOF as well as the time needed to get a solution of the given field problem which points out the need of simplified and still accurate methods.
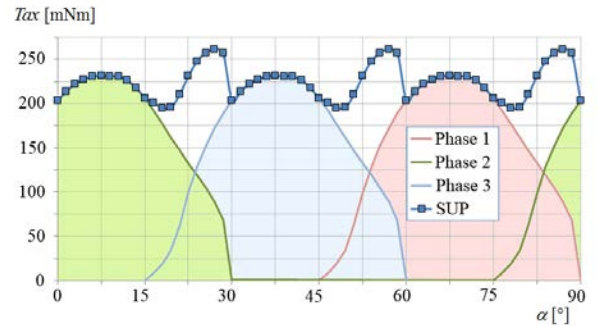

Fig. 4. Total torque acting on the rotor for three supplied phases as a result of superposition of single phase torque profiles (SUP).
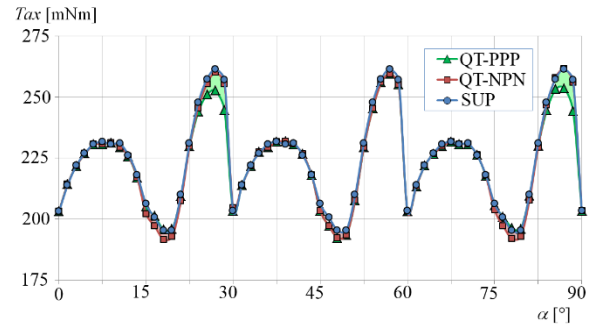

Fig. 5. Comparison of torque profile calculated in the quasi-transient analysis (QT) for PPP and NPN supply scheme with the total torque profile received from the superposition of single phase torque profiles (SUP).

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